Appendix C

Remedial Technologies and Process Options

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This appendix presents detailed descriptions of the remedial technologies and process options presented in Chapter 3. Sources for these descriptions are referenced at the end of appropriate sections. Several of the remedial technologies described in this appendix have already been tested and used at Lawrence Livermore National Laboratory (LLNL) Site 300. The remedial technologies already being used in ongoing removal actions or prototype remedial actions at Site 300 are identified in the following discussion.

C-1. Ground Water Remedial Technologies and Process Options

C-1.1. Ground Water Extraction

C.1.1.1. Ground Water Extraction from Wells

Ground water extraction wells may be either well points, naturally developed wells, or gravel-packed wells. Well points applied to shallow ground water (<30 ft) typically are manifolded to a header pipe and pumped with a suction system. Larger diameter wells are pumped most commonly with submersible electric pumps, although vertical turbine or pneumatic positive displacement pumps may also be used. Extraction wells that are to be used in a ground water recirculation system would most likely be constructed near the leading edge of a plume and coupled with injection wells located upgradient of the source. Extraction wells to be used for hydraulic gradient control might be installed upgradient of the plume [U.S. Environmental Protection Agency (EPA), 1991]. Extraction wells can also be used for plume containment, and are often used in combination with ground water treatment systems.

C.1.1.2. Ground Water Extraction via Siphons

Under appropriate conditions, ground water extraction can be accomplished without pumping, through the use of siphons. All principles are similar to pumping with the exception that topography is used to provide natural head to push ground water to the surface. This technology saves the cost of pumps and the energy to operate them.

C.1.1.3. Extraction from Trenches

For a description of this technology, refer to Section C.1.7.3.

C-1.1.4. Ground Water Extraction using Funnel and Gate with a Collector Basin

The funnel and gate concept was created to enhance the capture and collection of contaminated ground water in areas that do not lend themselves to typical pumping technologies. When traditional pumping works, the funnel and gate may be redundant and not as versatile. This technique involves the installation of sheet pile walls and grout curtains to funnel ground water to a single extraction point, eliminating further downgradient migration of contamination. A well is constructed or modified to create a collection and extraction point. The funnel is comprised of sheet pile walls and grout curtains forming a "V" shape. The intersection of the "V" points down gradient, with the extraction well at the intersection, and the open end encompassing the extent of any contaminated ground water flow.

For example, the sheet piles are driven down and keyed into the confining layer forming the initial "V" shape. The downgradient ends of the sheet piles tie into the extraction well structure and the upgradient ends terminate within the grout curtain. The grout curtain, which forms the outer edges of the "funnel", is created by the injection of grout under high pressure into a series of borings. The grout flows into the cracks and pores of the soil matrix like fluid but hardens creating an impervious barrier to ground water flow.

With the creation of the "funnel", a contaminant plume within a saturated aquifer is collected, treated, and prevented from migrating further downgradient. Collected ground water is pumped from the extraction well to the treatment facility.

C-1.1.5. Surfactant Injection

Surfactant injection is an innovative, *in situ* technique for enhancing removal of dense nonaqueous-phase liquids (DNAPLs) or highly sorbed contaminants from the subsurface. The technique is applied by pumping water, mixed with surfactants, into the ground water zone via injection wells. The surfactants cause a significant increase in the solubility of the DNAPLs by forming colloidal clusters (called micelles) in which the DNAPLs are solubilized. The DNAPLs go into solution to concentrations several orders of magnitude greater than their normal water solubility. The resulting water/DNAPL mixture can be pumped to extraction wells without the DNAPL becoming sorbed by soil particles, and treated with conventional ground water treatment systems (NETAC, 1992).

This technology is limited by subsurface heterogeneities, and the ability to control plume migration through injection/extraction schemes.

C-1.1.6. Electro-osmosis

Electro-osmosis is the phenomenon by which aqueous fluid flow through a porous medium is driven by an imposed electric field. When an electrical potential is applied across a wet soil mass, cations are attracted to the cathode (negative electrode) and anions are attracted to the anode (positive electrode). As the ions migrate they carry their water of hydration and they create a drag on the water around them. Since there are more cations than anions in a soil containing negatively charged clay particles, there is a net water flow toward the cathode (Mitchell, 1993). When the cathode is also an extraction well, it can be used to remove ground water delivered to it by electro-osmosis. To prevent dewatering and consolidation, water is

reinjected at the anode. Electro-osmosis has been shown to be effective in causing contaminants to migrate in low permeability sediments where pumping is slow and difficult (Nyer, 1996).

This technology is emerging, but is limited by the lack of full scale field applications and our ability to predict efficiency and economics.

C-1.2. *Ex Situ* Ground Water Treatment

C-1.2.1. *Gravity Separation/Skimming*

Gravity separation consists of separating contaminants from ground water by allowing gravity settling of liquids of different densities such as Light Non-Aqueous Phase Liquids (LNAPL). Ground water and LNAPL is pumped from the subsurface and fed to a settling vessel where the two phases are allowed to separate by gravity settling. The LNAPL is then removed by skimming the floating product.

C-1.2.2. *Granular Activated Carbon—Aqueous Phase*

Aqueous-phase granular activated carbon (GAC) adsorption is a well established ground water treatment technology which is generally effective for removing high molecular weight compounds and chlorinated solvents. Activated carbon removes contaminants from water by adsorbing them onto its surface. A GAC adsorption system consists of a packed column with an internal/diffusion system to distribute the water evenly through the carbon bed. Organic compounds adsorb onto the surface of the GAC as the water flows through the fixed bed. Desorbed compounds can then be thermally oxidized or driven off and collected for reuse. The spent GAC may be either disposed of as hazardous waste or thermally regenerated by heating the carbon in a natural gas-fired furnace, thereby completely desorbing the organic compounds from the surface of the GAC. After regeneration, the GAC is no longer considered a hazardous waste and may be reused. However, regeneration reduces the adsorptive capacity of GAC and the used material eventually must be disposed of and replaced. GAC consumption is dependent upon flow rates and contaminant concentrations. Aqueous phase GAC can be subject to clogging from carbonate precipitation or biofouling, therefore, pretreatment of the influent water stream may be required. Generally, GAC is cost effective for low flow and low concentration applications (Isherwood et al., 1991).

C-1.2.3. *Air Sparging*

Air sparging consists of forcing air through coarse air bubble diffusers into large tanks filled with contaminated water. The agitation of the water and contact with forced air promotes the volatilization of VOCs. This technology can be used in conjunction with vapor-phase GAC (Isherwood et al., 1991). High calcium and magnesium hardness, which occurs at Site 300, can clog the sparging tank components, reduce efficiency, and increase operating costs. Generally, air sparging has lower energy efficiency than air stripping, however, it is often better suited for low flow, batch treatment systems. Generally, aboveground air sparging is cost effective for low flow rates and high VOC concentrations, unless mineral content causes operating problems.

C-1.2.4. Air Stripping

Air stripping is a process in which VOCs are removed from water by bringing VOC-contaminated water into contact with air. This is commonly achieved with air stripping towers or trays. In conventional air strippers, contaminated water is sprayed into the top of an air stripping column. Water cascades down through packing material within the column, thereby increasing the surface area of the water. A blower forces an upward air stream through the water, transferring VOCs from water to air.

Tray aeration is achieved by spraying extracted ground water into an inlet chamber. The water flows along baffled aeration trays and air is blown up through small-diameter holes in the trays. A froth forms, creating a large mass transfer surface. The high air-to-water ratio causes the organic contaminants to volatilize into air, leaving reduced concentrations of VOCs in the water.

Air stripper design operation and maintenance must be tailored to the general water quality at the site. High calcium and magnesium hardness, which exists at Site 300, can clog the packed columns, reduce efficiency, and increase operating costs. This technology is usually used in conjunction with vapor-phase GAC to eliminate VOC discharge to the atmosphere.

The cost is dependent upon flow rates and VOC concentrations. Generally, air stripping is cost effective for high flow rates and high VOC concentrations, unless water hardness causes operating problems (Isherwood et al., 1991).

C-1.2.5. GAC—Vapor Phase

Vapor phase GAC treatment is used to remove VOCs from the vapor exhaust of a soil vapor extraction system or a ground water air sparging/stripping treatment system. The use of vapor-phase GAC is a well established technology for the removal of VOCs from vapor streams. GAC is effective over a broad range of constituent concentrations in the air stream, although the mass of organic compounds that will be adsorbed per unit mass of GAC increases as the concentration of the compounds in the air to be treated increases. High moisture content in the vapor and elevated temperatures can limit the sorptive capacity of carbon, thereby necessitating additional vapor treatment, such as a moisture accumulator installed upstream of the GAC canisters. The spent GAC may be either disposed of as hazardous waste or thermally regenerated by heating the carbon in a natural gas-fired furnace, thereby completely desorbing the organic compounds from the surface of the GAC. However, regeneration reduces the adsorptive capacity of GAC, and the used material eventually must be disposed of and replaced. Annual treatment costs associated with GAC can be quite high initially; costs decrease as VOC concentrations in the soil vapor decrease over time (Isherwood et al., 1991).

C-1.2.6. Ultraviolet (UV)/Oxidation—Aqueous Phase

UV/oxidation uses an oxidizing agent, such as hydrogen peroxide or ozone, and UV light as an agent to augment the dissociation of the oxidizing agent to a hydroxyl radical. By destroying the VOCs, UV/oxidation processes minimize the amount of waste that requires further treatment or disposal (LLNL, 1991). The process, however, is energy intensive.

One type of UV/oxidation technology is Perox-Pure™, a chemical oxidation technology that was demonstrated under EPA's Superfund Innovative Technology Evaluation (SITE) program at

the GSA operable unit. Over a three-week period in September 1992, about 40,000 gallons of VOC-contaminated ground water was treated in the Perox-Pure™ system. For the SITE demonstration, the Perox-Pure™ system achieved trichloroethylene (TCE) and tetrachloroethylene (PCE) removal efficiencies of about 99.7 and 97.1%, respectively. In general, the system produced an effluent that contained no detectable TCE, PCE, and 1,1-dichloroethane (DCA); with chloroform and 1,1,1-trichloroethane (1,1,1-TCA) slightly above detection limits. The system also achieved chloroform, DCA, and TCA removal efficiencies of 93.1, 98.3, and 81.8%, respectively. The treatment system effluent met California drinking water action levels and federal drinking water maximum contaminant levels (MCLs) for TCE, PCE, chloroform, DCA, and TCA at the 95% confidence level (U.S. EPA, 1993).

C-1.2.7. Ion Exchange

Ion exchange is a process in which target ions, such as perchlorate, nitrate, or uranium-bearing ions, can be removed from water. Contaminated water is pumped into tanks or large columns filled with ion-specific resin beads or hybrid resins for removing multiple contaminants from a single water stream. Ion exchange resins are composed of a polymer backbone attached to a functional group selected to attract the ion of concern. Typically, before the resin is exposed to the contaminated water, the functional group is bonded to a chloride ion. However, other ions may initially be bonded to the functional group, depending on what specific chemical species the contaminant occurs as in the water. When the contaminated water flows through the resin beads, the chloride ion is exchanged for the target ion of concern, which has a higher affinity for the functional group. These chloride ions enter solution and flow out with the effluent stream, while the exchanged target ions remain bonded to the functional group. When the resin becomes saturated with target ions, it is regenerated by rinsing the resin beads with a high concentration salt solution. Because of the extremely high percentage of chloride ions, the target ions are displaced, enter solution, and exit with the regenerating waste water. The waste water is then disposed and the resin is rinsed with clean water and returned to service.

Uranium can be found in ground water as a variety of dissolved species, depending on chemical conditions. At Site 300, due to the abundant dissolved oxygen and bicarbonate in the ground water, uranium typically occurs as uranium carbonate complexes. Prior to selecting the appropriate resin, column experiments must be conducted to determine which resin is most efficient and cost-effective in removing uranium from the extracted site-specific ground water. In addition to resins, other agents, such as zeolites, activated carbon, peat, phosphates, ferric hydroxides, and iron filings can be used to remove uranium from water streams. Colloids may also carry a significant component of the uranium observed in ground water at Site 300. Because of this, electrophosphoresis or ultrafiltration may also be applied to the water stream to remove colloids that may contain appreciable uranium.

When volatile organic co-contaminants are present in the water, this technology is typically preceded by an air stripping unit. Other contaminants and naturally-occurring ions may foul the resin beads and force more frequent regeneration of the resin. The ion exchange unit requires fairly high flow rates [15 to 25 gallons per minute (gpm)] to be effective. The higher the concentration of target ions, the quicker the resin will become saturated and require regeneration. The cost of resin replacement and disposal of regeneration wastes can be too high to make this a cost-effective technology.

C-1.2.8. Chemical and/or Biological Treatment

C-1.2.8.1.   Coupled Chemical/Biological Treatment.   Researchers at LLNL have developed an innovative technology for removing RDX from ground water (Knezovich et al., 1996). This coupled chemical/biological treatment process uses GAC to remove high explosive (HE) compounds from aqueous waste streams. The HE compound is desorbed from the GAC using a heated solvent or an alkaline solution that hydrolyzes the HE. The HE- or hydrolysate-laden effluent can then be treated using a denitrifying culture of microorganisms in a fixed-bed bioreactor. This technology has been successfully pilot-tested at Pantex Plant in Amarillo, Texas. Testing at Pantex verified the long-term efficiency and reliability of this technology to treat HE-laden aqueous waste streams in a continuous flow mode. This treatment technology removes the hazardous constituents from the GAC and allows the GAC to be regenerated for future use, thereby minimizing waste and reducing costs.

C-1.2.8.2. Bioremediation. Bioremediation can involve the use of microbes to degrade organic compounds in contaminated ground water. Under favorable conditions, microorganisms may be capable of completely degrading many organic compounds into carbon dioxide and water, or organic acids and methane.

The applicability of bioremediation depends on the nature of site contaminants. Petroleum compounds, such as gasoline and diesel fuel, are known to be readily biodegradable. Other biodegradable contaminants include alcohols, phenols, esters, and ketones. Chlorinated compounds are more difficult to biodegrade, especially as the number of chlorine molecules increases. Bioremediation of large, heavily chlorinated compounds such as polychlorinated biphenyls (PCBs) is slow and therefore generally impractical.

Both aerobic and anaerobic processes are applicable to the degradation of hazardous materials. Many chlorinated solvents, such as PCE, TCE, and TCA, are recalcitrant in aerobic conditions. These compounds may, however, be degraded under anaerobic conditions. The degradation of these compounds involves reductive dehalogenation, in which chlorine is replaced with hydrogen, to form new compounds. Chlorinated alkenes can be mineralized during co-metabolism by methane-utilizing bacteria (methanotrophs) in aerobic environments. In other contaminated systems, some chlorinated compounds can be reductively dehalogenated to produce intermediate products that can then be degraded further using aerobic processes.

Bioremediation is often combined with other technologies, either by design, as with pump-and-treat, or as part of a treatment train, following soil flushing (U.S. EPA, 1991). Extracted water can be fed to an *ex situ* bioreactor. Seed bacteria that are capable of degrading the contaminant of concern are introduced to the bioreactor. For compounds that are aerobically biodegraded, oxygen and nutrients are typically introduced to the water.

Biological treatment is often used in conjunction with other treatment methods. For example, for specific organic compounds, additional treatment or "polishing" steps, such as carbon adsorption might follow treatment in the bioreactor. Ideally, the bioreactor removes most of the compounds at a lower cost, and the carbon system ensures that no contaminants are discharged. While *ex situ* bioremediation has been demonstrated as a fairly low cost means of treating compounds which aerobically degrade, this technology has proven to be less effective for remediating chlorinated solvents.

Other contaminants found at Site 300 that are candidates for bioremediation include nitrate (NO_3) and perchlorate (ClO_4). Treatment efficiencies for these and other constituents via bioreactor technology using indigenous bacteria cultured from the Site 300 environment are currently being determined.

C-1.2.8.3.   Ground Water Treatment using Zero Valent Iron Filings.   Chlorinated volatile organic compounds (CVOCs) in ground water can be treated using zero valent iron filings. This technology entails extracting ground water and piping the water to an above ground tank which is filled with granular cast iron (treatment media). The iron reduces the CVOCs to ethane, ethene, methane, and chloride ions in the degradation of TCE, which is the primary contaminant of concern.   This zero valent iron enhances abiotic degradation of CVOCs and is essentially a reductive dechlorination process, which uses the granular cast iron as the reducing agent.   The degradation of CVOCs is the result of surface activated reactions, where the reductive dechlorination process requires the adsorption of the CVOCs onto specific active surfaces on the iron filings.

A similar degradation process can be utilized for nitrate (which may exist in combination with TCE) in ground water. In this process, the nitrate will be reduced to ammonium and possibly to nitrogen by the zero valent iron process.

The destruction of CVOCs is dependent on influent concentrations, residency time across the treatment media, flow rates, and target effluent concentrations. Studies have shown that with TCE concentrations up to free phase product, iron filing treatment media systems can be designed to produce effluent concentrations at 5 µg/L and below.

Zero valent iron filings is currently being tested at LLNL for nitrate remediation.

C-1.2.8.4.   Phytoremediation.   Phytoremediation is the use of plants and plant systems to remediate soil and water containing metals, and/or organic chemicals. These plant systems include microbial organisms that are part of the remediation process. Some of these plant systems already exist and some are designed and constructed to exploit the various processes available to remediate the target metal or chemical (McMutcheon, 1998). LLNL is presently testing "Engineered Ecoassimulation", which is the use of indigenous plant systems for the uptake of nitrate-laden ground water. LLNL is also testing a "Cascading Modular System." This is a series of containers filled with various materials to treat nitrate-laden ground water in a step-wise fashion. The water is cascaded through the following materials and plant systems: 1) gravel, 2) sand, 3) cattails, 4) sedge, and 5) aquatic plants such as algae.

Another specific type of phytoremediation is a "Constructed Wetland." This technology is discussed in Section C-1.2.8.5.

C-1.2.8.5.   Constructed Wetlands.   Constructed wetlands provide a means for destroying contaminants (i.e., nitrates) rather than transferring them from one medium to another. Constructed wetlands use the interaction of rhyzomous vegetation and anaerobic bacteria to denitrify nitrate-bearing water. Although a variety of designs may be employed, data indicate that subsurface flow systems are significantly more effective than surface flow systems (Hammer, 1989).

Three primary components are required in a subsurface flow constructed wetland: an impermeable layer, a gravel layer that provides a substrate for the vegetation root zone, and an

above-surface vegetation zone. The impermeable layer prevents infiltration of the waste water. The waste water flows and denitrification occurs in the gravel layer and associated root zone. The above-surface vegetative zone contains the green, photosynthetic portion of the plants that provide the initial carbon fixation and ultimate carbon supply to the denitrification process. Nitrate-bearing water is pumped or gravity drained through a piping manifold into one end of the constructed wetland to evenly distribute the water and prevent channeling. Water then gradually flows about one foot below the surface through the gravel layer and the root zone, and discharges from the distal end of the constructed wetland.

The capacity of a constructed wetland can be affected by precipitation and evapotranspiration rates, the root depth of the chosen vegetation, and areal extent. Areal extent can be limited by local topography or cultural features. This technology may also be effective in treating HE compounds and perchlorate.

C-1.2.9. Technologies for the Removal and Concentration of Tritium in Water

Tritium cannot be chemically treated to render it non-radioactive. Therefore, isotope separation techniques to concentrate the tritium into a smaller volume are the only methods available for tritium-bearing water treatment. In tritiated water (HTO), the substitution of an atom of hydrogen (atomic mass of 1) with the three-fold heavier isotope, tritium, causes variation in most of the chemical and physical properties of the water. This is a consequence of the corresponding mass variation. All of the processes employed for isotopic separation take advantage of the mass variation between "typical" water and tritiated water.

A generalized separation element can be viewed as a black box into which flows tritiated water of a certain isotopic composition. Out of the separation element flow two streams, one containing a higher and one a lower percentage of the tritium than the influent stream. For ground water restoration, the goal is to concentrate the tritium in a small volume and to produce a large mass of water with little-to-no tritium that can be released to the environment with no adverse effects.

Although isotopic separation processes are based on differing principles, the common goal is to multiply the elementary separation effect to achieve a pre-determined final isotopic content in a treated volume of tritiated water. Thus, researchers have developed a mathematical framework, wherein a separation factor defines the increase of the desired isotope after one run through a separation element. One or more separation elements connected in parallel define a stage. The desired isotopic concentration can be achieved by connecting several stages in series. These data are important for estimating total treatment costs.

The following technologies for tritium removal from water are currently available or are in experimental stages, and may become available, if proven effective. These are:

- Electrolytic enrichment,
- Thermal diffusion,
- Vapor phase catalytic exchange/cryogenic distillation,
- Liquid water distillation,

- Combined electrolysis/catalytic exchange,

- Membrane filtration,

- Isotopic exchange, and

- Resin separation.

The first five technologies were developed to enrich or treat tritium-bearing waters for analytical or nuclear power plant applications, where massive quantities of water might require treatment. Thus, these technologies, while proven and available, require a large scale and have very large capital and operating costs. The final three technologies are in proof-of-principle and experimental stages. Therefore, it is not yet possible to evaluate their applicability to tritium-bearing ground water at Site 300. However, the current understanding of what would be required to implement any of these technologies at Site 300 indicates that at least several of them would be very expensive.

A more complete overview of the various treatment technologies can be found in McConachie and Brown (1996). LLNL is currently drafting a letter report that will document the current state of knowledge of water treatment technologies for tritium.

C-1.3. Disposal of Treated Water

C-1.3.1. Permitted Discharge to Surface Water, Sanitary Sewer/Storm Drain, or Sewage Pond

Treated ground water from remediation systems may be discharged to nearby surface water, or a sanitary sewer or storm drain under a National Pollution Discharge Elimination System (NPDES) permit. A portion of the treated water might also occasionally be discharged to a sewage treatment pond located in the southeastern portion of Site 300. Discharges to the pond would occur only occasionally as makeup water during summer months. Any discharges would be regulated by a NPDES permit waste water discharge requirements.

C-1.3.2. On-Site Surface Discharge

Ground water treatment system effluent can potentially be discharged directly to the ground surface onsite. These discharges of treated water are regulated under Substantive Requirements issued by the California Regional Water Quality Control Board. The treated water can be sprayed onto the ground where it rapidly infiltrates.

C-1.3.3. Reinjection

Reinjection wells can function as a means to discharge treated ground water, hydraulically control plume movement, and reduce cleanup times. The reinjection of treated ground water can be an efficient cost-saving measure. However, the quality of the reinjected water is important because of potential for recontamination and/or scaling from precipitates, such as carbonate. Scaling and/or microbially-induced fouling can reduce the efficiency of the injection well and require periodic maintenance. For purposes of flow control, ground water reinjection might need to take place within the capture zones of ground water extraction wells (U.S. EPA, 1991).

C-1.3.4. On-site Recycling/Reuse and Offsite Uses

On-site recycling and reuse of treated ground water consists primarily of the use of the water for irrigation of vegetation at Site 300. Currently, well water is used for this purpose. In the past, adjacent property owners have also expressed interest in using treated ground water for irrigation purposes on their ranches. Potential legal issues have thus far prevented the use of treated water offsite.

C-1.3.5. Air Misting

Air misting is a method of discharging treated ground water by forcing it through spray heads that separate the water into fine droplets (i.e., atomization) as it is expelled into the air. This process allows maximum areal dispersion of discharge. This discharge process eliminates problems associated with surface discharge (e.g., erosion). Misting is most applicable for low flow rates. This process is being applied as part of the Site 300 Building 834 CERCLA Removal Action and is being used to discharge treated well development and sample purge water at Building 833.

C-1.4. Disposal of Separated Product or Treatment Wastes

Separated free product, spent GAC or resin containing sorbed contaminants are generally shipped offsite for regeneration or disposal at a RCRA-permitted facility. Contaminants may be desorbed from the GAC or resin and destroyed. The regenerated GAC and resin can then be reused.

C-1.5. *In Situ* Ground Water Treatment

C-1.5.1 Air Sparging

In situ air sparging requires either trenching to lay a shallow network of air injection and extraction piping and then backfilling, or vertical and/or horizontal drilling to construct a deep subsurface network of piping. One difficulty in using the *in situ* method is plume control. The air may diffuse away from collection points and mobilize the contaminants in an undesirable direction. Also, the effectiveness of *in situ* air sparging can be significantly reduced by the vertical channeling of the injected air along vertical preferential flow paths. This method can also be expensive when horizontal drilling is used, because of the specialized nature of horizontal drilling.

C-1.5.2. Permeable Reactive Barrier

This technology involves the use of a subsurface reactive barrier to remediate ground water contaminants *in situ* as ground water passes through the reactive barrier. A trench is excavated in the pathway of the contaminant plume. The trench is then filled or partially filled with a substance designed to react with the contaminant of concern in ground water. As ground water passes through the reactive material, the contaminant is destroyed or altered to a non-hazardous by-product. An example of materials that may be used in a permeable reactive barrier is iron filings which destroys TCE and its degradation products. This type of technology is generally

best suited to narrow plumes that flow through or can be directed through a plume pathway of relatively short horizontal distance.

The concept of an *in situ* permeable reactive barrier for the removal of uranium from ground water involves cutting a fully-penetrating trench through a cross-sectional area of a uranium plume in a shallow alluvial aquifer. If it is impractical to construct a trench across the full width of a uranium plume, a funnel-and-gate system can be installed to increase the capture width of the reactive barrier. Prior to emplacement of the reactive materials, the trench can be kept open with shoring or a caisson. The trench would be filled with a porous material (sand or gravel) impregnated with one or more of the following immobilization agents: activated carbon, organic resins, ferric hydroxides and orthohydroxides, peat, phosphates, titanium oxide, zeolites, or iron filings. Several recent studies indicate that iron filings are very effective in reducing uranium concentrations to lower than background levels (DOE, 1998). When water flows through the iron filings, the dissolved oxygen is exhausted by iron oxidation. The uranium carbonate complexes are then quickly converted to insoluble uranium hydroxide compounds and precipitate out of the ground water. To verify the continued effectiveness of the barrier, monitor wells would be installed immediately up- and downgradient of the barrier, and would be monitored for uranium and other index parameters. Prior to selection and design of a permeable reactive barrier, column and bench-scale testing would be performed to select the most efficient and cost-effective material for *in situ* removal of the uranium in ground water. Such tests are also required to determine the effective life of the selected reactive materials and the permanence of the uranium precipitates formed. Additionally, a mechanism must be included in the design for the removal and replacement, or regeneration, of the reactive materials. Colloids are also a concern. Thus, an agent that can immobilize uranium-bearing colloids would be included in the reactive material selected.

C-1.5.3. Enhanced In Situ Bioremediation

Enhanced *in situ* bioremediation is an innovative technique for the remediation of dissolved, adsorbed, and/or separate phase contaminants through the injection of nutrients that stimulate microbial growth. The technique can be applied by pumping water spiked with appropriate carbon and energy sources into the contaminated aquifer via injection wells (Devlin and Barker, 1994). Injected nutrients promote the growth and activity of microorganisms that may directly or indirectly participate in the biological destruction of pollutants.   Ideally, the process yields water, carbon dioxide and inorganic salts as the sole, innocuous end products.

Effectiveness and implementability of this technology are limited by subsurface heterogeneities and delivery problems such as proper injection schemes and problematic and sometimes costly trenching and shoring of unconsolidated and bedrock materials.

C-1.6. Containment

C-1.6.1. Slurry Walls

Slurry walls are often utilized in combination with hydraulic controls or pump-and-treat technologies to focus ground water recovery on a particular area or to enhance containment measures. This results in an optimal concentration of treated water, decreased treatment costs,

and shortened cleanup times. Slurry walls can also be used with capping technologies to fully confine a waste area and to prevent clean water from leaching through the wastes.

A slurry wall is constructed by excavating a narrow vertical trench, typically 2 to 4 ft wide, and backfilling with a low hydraulic conductivity material to contain a waste source and to prevent contamination from migrating off site. As excavation proceeds, the trench would be filled with a bentonite-water slurry which stabilizes the walls of the trench, thereby preventing collapse. The slurry penetrates into the permeable soils and creates a filter cake on the trench walls that seals the soil formations, prevents slurry loss, and also contributes to the low permeability of the completed slurry wall. This narrow trench is then backfilled with a second slurry mixture. Slurry walls are differentiated by the materials used to backfill the slurry trench. If a mixture of soil and bentonite is used, then the wall is known as a soil-bentonite (SB) slurry wall. In some cases, the trench is excavated under a slurry of portland cement, bentonite, and water, and this mixture is left in the trench to harden into a cement-bentonite (CB) slurry wall. This technique can be used at sites where there is adequate open area for the mixing and placement of the soil-bentonite backfill, where increased wall strength may be necessary, or where extreme topography changes make it impractical to grade a site level (U.S. EPA, 1991).

C-1.6.2. Grout Curtain

Grouting is a process by which a fluid material is pressure injected into soil or rock to reduce fluid movement and/or impart increased strength. Grouts accomplish this through their ability to permeate voids and gel or set in place. Grouting can be used to control the movement of ground water and to solidify or stabilize a soil mass. Grout injected into a soil mass reduces the permeability of the deposit. Grout curtains can be created in unconsolidated materials by pressure injection.

Grout types are divided into two general classifications: particulate or suspended grout and chemical grout. Particulate grouts are fluids that consist of a suspension of solid material, such as cement, clay, bentonite, or a combination of these materials. These materials are usually the more viscous of the available grouting materials and have the largest particle size. Chemical grouts are frequently classified into two major groups: silica- or aluminum-based solutions and polymers. Chemical grouts rely on polymerization reactions to form hardened gels. They have initially low viscosities and can therefore be used in finer grained soils. (See U.S. EPA, 1991).

C-1.6.3. In Situ Stabilization of Landfill Wastes

Several methods are available or under development for the stabilization of landfill wastes. The general idea is to lower the permeability of the body of the waste, and thus less susceptible to leaching. A variety of solidifying agents are currently available (portland cement, blast furnace slag, polymers, asphalt, paraffin, and polyethylene) that can be injected under pressure into a landfill waste to fill all the void space. If injection is impractical, or likely to be ineffective, the solidifying agents can be mixed into the waste with large diameter proprietary auger equipment. This latter process has the drawback of potentially bringing landfill contents into contact with the atmosphere. Workers at several facilities and in industry are working on innovative materials that can stabilize buried waste of various particle sizes.

Another technique is *in situ* vitrification, where the buried waste is melted using electrical power for heat. An array of electrodes is inserted into the buried waste. Usually flaked graphite

and glass frit are placed between the electrodes to conduct the initial current. Upon heating, temperatures in the waste rise to 1600-2000 degrees F. As the waste melts, it forms impermeable glass which encapsulates the waste and makes leaching of contaminants to ground water impossible. Major drawbacks include volatilization of waste chemicals (such as tritiated water) to the atmosphere and possible de-vitrification of wastes to a more leachable condition over time.

Conceptually, this process could be used at the base of a landfill, forming a "bottom grout," which would prevent migration of contaminants into the formations or ground water below. This approach has not yet been fully demonstrated, but holds some promise for the future.

LLNL will continue to investigate new technologies for *in situ* stabilization that may be applicable at Site 300.

C-1.7. Hydraulic Control

In a hydraulic control response action, technologies may be used to avoid contamination of clean ground water or further contamination of ground water by preventing the ground water from reaching a source area. Section C-1.1 discusses the role extraction wells can play in containing contaminant plumes.

C-1.7.1. Surface Cover/Pit Capping

A surface cover placed over buried waste or a contaminant plume can limit or preclude surface water infiltration and minimize the generation of a leachate. A surface cover also controls the emission of gases and odors, reduces erosion, and may improve aesthetics. It provides a stable surface that prevents human exposure to wastes, and may be necessary when contaminated materials are left in place at a site. In situations where the waste is entirely above the ground water table, a properly designed cover can prevent the entry of water into the landfill or surface impoundment due to direct infiltration. Under CERCLA, capping is performed when potential hazards and/or high costs associated with extensive subsurface contamination at a site makes excavation and removal of wastes impractical. Capping is often performed in connection with ground water extraction or containment technologies (U.S. EPA, 1991).

C-1.7.2. Subsurface Interflow Interceptor System

A subsurface interflow interceptor system can potentially passively capture interflow in upgradient colluvial material and allow the captured water to reinfiltrate downgradient. Interflow includes transient water flow at the interface between colluvium and bedrock during times of intense infiltration. The system design could include an upgradient subdrain trench, a buried conduit pipe, extraction wells, and an infiltration gallery.

A subdrain trench might consist of a gravel-filled trench with a perforated pipe at the bottom to capture subsurface upgradient ground water interflow. The perforated pipe would be sloped to provide gravity drainage to the conduit. The extent of capture and the flow rates can be calculated, based on subsurface ground water flow data. Design studies are necessary to choose materials and size the perforated pipe to assure that the pipe could resist damage by nearby activities (e.g., firing table explosions). Modeling is used to determine design details of the subdrain trench.

A conduit consists of a buried pipe to transport the water captured by the subdrain trench to a discharge, which in most cases will be an infiltration gallery. The pipe would be sloped to provide gravity drainage. The pipe diameter, burial depth, and trench backfill materials are determined using the model results required for subdrain trench design.

An infiltration gallery consists of an excavated region backfilled with gravel to allow water from the conduit to be temporarily stored in the pores of the gravel until it percolates into the downgradient native soil and bedrock. The results of calculations described above, as well as geologic studies and percolation tests, would be used to determine the site location and design details.

The purpose of any ground water interceptor system would be to prevent inundation from below of an unlined landfill. The degree to which inundation may occur from a general rise in ground water levels surrounding the landfill, not just from upgradient flow, may limit the applicability of such systems. Other limitations come from the difficulty of designing a system to adequately intercept the flow, which is limited by aquifer materials, permeability, ground water depth, terrain, etc.

C-1.7.3. Interceptor Trenches

Interceptor trenches function like drains. Trenches and drains can be either active (pumped) or passive (gravity flow). Trenches and drains may be used in the containment mode for collection of second-phase pollutants that flow on the water table (e.g., LNAPLs). Passive systems are usually left open with an installed skimming pump or settlement tank for removal of the pollutant.

The benefits of using interceptor trenches or drains are: (1) they have a relatively simple construction, (2) they are relatively inexpensive to install, (3) they are useful for collecting contaminants in poorly permeable soils, (4) they are useful for intercepting landfill seepage and runoff, (5) their large wetted perimeter allows for high rates of flow, and 6) they can be monitored to recover pollutants.

The limitations of interceptor trenches or drains are: (1) they are open systems and therefore require safety precautions to prevent fires and explosions, (2) they are not useful for sites where contamination is deep, and (3) they may interfere with other operations at a facility (U.S. EPA, 1991).

C-1.7.4. Ground Water Extraction and Re-injection

Hydraulic control of tritium plumes by extracting ground water from the leading edge of a tritium plume and re-injecting upgradient was evaluated. The re-circulation process as a remedial measure for hydraulic control of the tritium plumes poses the following problems:

1. The re-injection of tritiated water into areas with clean ground water would result in the increase in the extent of contamination in ground water.

2. Re-injection tritiated water near the source area could increase the hydraulic gradient and could spread of the existing contaminated waters into clean areas further and faster than without such injection.

3. The re-injection of tritiated water in areas where ground water is present at shallow depths, such as the Pits 3&5 area, could exacerbate the inundation of the source area during periods of high rainfall and result in further contaminant releases.

4. Short-term human health and ecological risks are increased by bringing tritium to the surface.

In the Pits 3 and 5 area, the portion of the tritium plumes with activities above drinking water standards (20,000 pCi/L) is currently stable and the tritium plumes do not currently pose a risk to human or ecological receptors. Due to concerns that hydraulic control through re-circulation could further mobilize or spread the plume, and increase risk, this general response action was not retained as a primary remedial measure for the tritium plume at this time.

However, re-injection was retained as a component for remedial measures that extract and treat ground water containing multiple contaminants such as VOCs, nitrate, perchlorate, and tritium. It would be necessary under this type of remedial scenario, following treatment of the VOCs and other contaminants for which a viable treatment technology exists, to re-inject the tritiated water. In addition, safety precautions would need to be implemented to prevent exposure to tritium during the extraction and re-injection process. The efficacy of this remedial strategy would depend on the volume and tritium levels in the water to be re-injected, as well as the re-injection location. Modeling would need to be conducted prior to implementation of this type of remedial action to ensure that re-injection would not result in inundation of a source area and/or further mobilization of the tritium plume. If the modeling results indicate that the re-injection of even limited volumes of water could potentially result in further releases and/or the spread of the tritium plume, the implementability of this remedial strategy may be limited.

C-2. Soil and Rock Remedial Technologies and Process Options

C-2.1. Soil Vapor Extraction

C-2.1.1. Active Soil Vapor Extraction

Active soil vapor extraction consists of applying a vacuum to one or more vadose zone extraction wells to enhance volatilization and removal of high-volatility contaminants. Industry experience indicates that this process is very effective for remediating most chlorinated solvents and volatile fuel hydrocarbons. Induced soil vapor extraction can be used in conjunction with ground water extraction.

The properties of vadose zone sediments, such as permeability and moisture content, and the areal extent and depth of contamination determine the design of a soil vapor well field. This technology is typically used in conjunction with vapor phase GAC treatment to prevent the release of VOCs to the atmosphere. Induced soil vapor extraction can also be used to extract VOCs released in conjunction with ground water remediation using innovative *in situ* air sparging.

Drawbacks to this extraction technology include the uncertainty in predicting the time required to achieve the remedial objectives and difficulties in extracting all hazardous materials

from a heterogeneous subsurface environment. In these situations, other technologies may be required in conjunction with soil vapor extraction. The treatment of air emissions can also be a significant operational expense (Isherwood et al., 1991).

C-2.1.2. Passive Soil Vapor Extraction

Passive methods of soil vapor extraction utilize the difference in pressure between the soil gas and the atmosphere to induce air flow in one direction or another. Use of a one way valve restricts the direction of air flow. Using this method, VOC laden soil vapors can be brought to the ground surface for treatment and discharge. This technology is limited by geophysical parameters, atmospheric pressure fluctuations and wind speed. Air flow is significantly less than that resulting from active extraction. Treatment of air emissions are similar to the active system.

Testing of this method has been conducted at DOE's Hanford and Savannah River Sites (Rossabi, 1993), and INEL (Daily, 1995).

C-2.1.3. Dual-phase Extraction

Dual-phase extraction technology can be used to extract contaminants from saturated soil, soil vapor and ground water. This technology uses a dual-phase vacuum pump to apply a high vacuum to a conventional ground water well. The vacuum is applied through a small diameter pipe inserted through a sealed wellhead. The pipe is inserted below the water table to a depth at which drawdown is desired. Ground water is extracted from the well through the pipe, eventually dewatering the well. When the well is dewatered below the pipe end, soil vapor is pulled through the well screen. Drawdown is maintained in the well as droplets of water are entrained in the high velocity vapor flow moving up the extraction pipe. Contaminants in both soil and ground water are concurrently extracted during this process. (Duffney et al., 1994).

C-2.1.4. Simultaneous Ground Water and Soil Vapor Extraction

A simultaneous ground water and soil vapor extraction systems can remove contaminated ground water and soil vapor from the same well. A standard electric submersible or pneumatic pump connected to a pipe is placed in the well below the water table at a depth at which drawdown is desired. Ground water is extracted through the pipe and fed to a ground water treatment system. At the same time, a vacuum would be applied to the well bore using a liquid ring vacuum pump. Soil vapor is extracted from the well bore through a separate pipe and is treated in a vapor treatment system. Typically, to avoid pulling water into the soil vapor treatment system, ground water extraction is conducted for a period of time prior to initiating soil vapor extraction. After sufficient drawdown is achieved, soil vapor extraction would be initiated with the ground water pump cycling on and off, as needed, to keep the well dewatered. The use of this technology may be limited by well yield and permeability of the sediments.

C-2.2. Thermal Enhancement

C-2.2.1. Steam Flooding

Steam flooding is an adaptation of oil-field technology that uses steam injection to enhance the recovery of hydrocarbons from the subsurface. Steam injected through multiple wells on the

perimeter of a plume can volatilize contaminants, thermally desorb contaminants in permeable zones, and displace them toward one or more central recovering wells (Siegel et al., 1992). This technology has been combined with Joule heating at the LLNL Main site to enhance volatilization in the low-permeability zones not penetrated by steam. This combined process is called "Dynamic Stripping."

This technology is limited by subsurface heterogeneities, the ability to control plume migration through injection/extraction schemes, and energy consumption.

C-2.2.2. Joule Heating

Joule heating is an experimental remediation technology developed by LLNL to enhance the removal of VOCs from soil. An experiment using this method to remove TCE was conducted at the Building 834 operable unit in the summer of 1992. Six electrodes were buried in shallow boreholes heating an area approximately 7 meters (m) in diameter and 4 m deep. Large alternating electric currents were passed through the soil, resulting in a decrease in TCE soil vapor concentrations from 130 $ppm_{v/v}$ to about 5 $ppm_{v/v}$ over a period of 25 days (Buettner, 1993).

This technology is limited by subsurface heterogeneities, the ability to control vapor capture, and energy consumption.

C-2.2.3. Hot Air Injection

Hot air injection is an innovative technology that can raise soil temperatures and drive off VOCs; however, due to the very low heat capacity of gases, it has limited application. Generally, with the airflow rates used in soil venting, air must be warmed to several hundred degrees centigrade to add sufficient heat to warm soils at a rate adequately high to be usable. The low heat capacity of air requires very high airflow and/or high air temperature to provide effective soil heating. High air flow is typically not practical or compatible with the overall treatment process, and well construction to allow very hot air injection may be difficult and expensive.

Hot air injection could reduce the effectiveness of *in situ* biodegradation. A temperature rise of more than 20 to 30 degrees Celsius (°C) (36 to 54°F) above ambient temperatures could inhibit growth of or kill off microorganisms near the injection point .

High soil temperatures help offset the low heat capacity of the air, but create other problems. To carry significant amounts of heat in air, temperatures need to be above 300°C (570°F). These temperatures can require substantial insulation to control heat losses in the piping connecting the inlet well. Also, the high temperatures needed can damage the materials used in typical monitor wells. For long-term use of high-temperature air injection, new and much more costly injection well designs are likely to be required.

Another heat source that has been used to generate hot air is solar heating. Air is drawn through a flat plate solar collector by a blower, which then discharges to an air injection well. The air temperature increase available from the collectors is limited. This system is reportedly used to enhance biodegradation rates by moderately increasing the soil temperature (Billings, 1991).

Hot air injection has also been used in conjunction with steam heating to ensure that the stripped organics remain in the vapor stream. However, air injection in these systems follows steam injection, and its purpose is to maintain organics in the vapor state; hot air is not injected for bulk soil heating (Smith and Hinchee, 1993).

C.2.3. *Ex Situ* Soil Vapor Treatment

C-2.3.1. *Granular Activated Carbon—Vapor Phase*

Carbon adsorption using vapor phase GAC is a widely used vapor treatment technology used in conjunction with soil vapor extraction. With few exceptions, most VOCs can be effectively removed from the vapor exhaust of a soil vapor extraction system using a GAC system. GAC is effective over a broad range of constituent concentrations in the air stream, although the mass of organic compounds that will be adsorbed per unit mass of GAC increases as the concentration of the compounds in the air to be treated increases. High moisture content in the vapor and elevated temperatures can limit the sorptive capacity of carbon, thereby necessitating additional vapor treatment, such as a moisture accumulator installed upstream of the GAC canisters. Spent GAC can be disposed of as hazardous waste, regenerated on site using steam, regenerated in an off-site kiln, or incinerated in an off-site furnace. However, regeneration reduces the adsorptive capacity of GAC. Annual treatment costs associated with GAC can be quite high initially; costs decrease as VOC concentrations in the soil vapor decrease over time (Isherwood et al., 1991).

C-2.3.2. *Thermal Oxidation*

The vapor emissions produced by soil vapor extraction or ground water treatment containing VOCs or fuel hydrocarbons (FHCs) can be controlled by passing the vapor through a thermal oxidation unit. There the air containing the organic vapors is heated to a temperature sufficient to completely oxidize the compounds. This technique is most easily applied to mixtures of air and fuel hydrocarbons in which the oxidation products consist of water and carbon dioxide. Chlorinated solvents, such as TCE, may also be thermally oxidized, although additional treatment of the exhaust gas from the thermal oxidation unit may be required to remove the hydrogen chloride produced. In most cases, the concentrations of organic compounds in the emissions from the soil vapor extraction operations will not be sufficient to maintain combustion, so an auxiliary source of fuel, such as propane or natural gas, must be supplied to produce enough heat. The major advantage of this system is that almost complete destruction (often over 99%) of the VOCs or FHCs can be achieved on site. In addition, this technology may be more economic than GAC treatment of the vapor phase for high concentrations in vapor vented over extended periods. The disadvantages are the capital cost for the thermal oxidation system and the cost of auxiliary fuel (Isherwood et al., 1991).

C-2.3.3. *Catalytic Oxidation*

Catalytic oxidation is similar to the thermal oxidation process except that the oxidation occurs in the presence of a catalyst, which allows the oxidation to occur at much lower temperatures. Use of a catalyst can have the advantage of reducing the quantity of auxiliary fuel required for the oxidation unit. However, catalysts may be susceptible to fouling and poisoning, particularly in the presence of chlorinated solvents. Recently developed catalysts are available

that are not degraded by chlorinated solvents. As with thermal oxidation, hydrogen chloride may have to be removed. The capital cost for installation can be weighed against the lower operational costs compared to thermal oxidation. Close operator attention or automated protection is generally required to prevent catalyst damage.

Catalytic oxidation is commonly used for the destruction of fuel hydrocarbon vapors. This method is not applicable to chlorinated solvents because toxic daughter products may be created in the process (Isherwood et al., 1991)

C-2.3.4. UV/Oxidation—Vapor Treatment

A UV/oxidation process is the photo-oxidation of VOCs in air using an ultraviolet source, such as a Purus xenon flashlamp. The flashlamps have greater output at 200–250 nm than medium-pressure mercury lamps at the same power and therefore cause much more rapid direct photolysis of VOCs, including methylene chloride, chloroform, carbon tetrachloride (CCl_4), 1,2-dichloroethane (1,2-DCA), TCA, Freon 113, and benzene. The observation of quantum yields greater than unity indicate the involvement of chain reactions for TCE, PCE, 1,1-DCE, chloroform, and methylene chloride.

Two full-scale air emissions control systems for TCE were constructed by Purus and tested at a LLNL. The systems were operated at flash frequencies of 1–30 Hz, temperatures of 33–60°C, flows up to 300 scfm (260 ppm$_{v/v}$ TCE) and concentrations up to 10,600 ppm$_{v/v}$ (100 scfm). Residence times ranged from 5 to 75 seconds. In all cases, except at the lowest flash frequency, greater than 99% removal of TCE was observed. Careful attention was paid to product formation and mass balances. The main initial photo-oxidation product of TCE was dichloroacetyl chloride, which upon further photolysis was converted in part to dichlorocarbonyl (phosgene or DCC) and ultimately to hydrochloric acid, carbon dioxide, and possibly carbon monoxide. Further treatment of photo-oxidation products was recommended for full-scale operation (Johnson et al., 1992).

C-2.3.5. Resin Sorption

Resin adsorption-regeneration for vapor treatment is an innovative system that traps VOC vapors on an adsorbent resin bed. The advantage of this system is its on-site regenerative capacity. Typically, a resin adsorption-regeneration system consists of one or more resin beds that are on line while another bed is being regenerated in a desorption cycle. The resin beds can be automatically switched between adsorption and desorption cycles. Desorption can be accomplished using a combination of temperature, pressure, and a carrier gas. During the desorption cycle, the VOCs trapped in the adsorbent resin material would be removed, condensed, and transferred in liquid phase to a storage tank.

The resin adsorption-regeneration system has two advantages over the conventional carbon treatment system. Because the adsorbent material can be regenerated on site, the cost is much lower than GAC, which typically must be transported off site as hazardous waste for disposal or treatment. Although on-site carbon regeneration is feasible, the carbon has limited reuse capacity before replacement. Carbon regeneration also produces acids when treated for VOCs, thus causing corrosion problems. The claim for the resin adsorption-regeneration system is that the adsorbent beds may be recycled in excess of 2,000 times with no measurable loss of adsorption capacity (Purus, 1993). In addition, activated carbon's capacity to adsorb VOCs is

significantly affected by moisture. The resin adsorption-regeneration system adsorbent resin beds have a high tolerance to water vapor, thereby allowing treatment of vapor streams that have a relative humidity of greater than 90% with minimal impact on adsorption efficiency. These two factors would lower the operation and maintenance treatment costs and could make the resin resorption-regeneration system more cost effective and efficient for long-term treatment.

C-2.3.6. Electron Accelerator—Vapor Phase

Electron accelerator is another innovative technology that might be used for the radiolytic remediation of VOCs. In this process, a contaminated vapor stream would be irradiated with a small electron beam created by an electron accelerator, thereby reducing the concentration of the VOC. The level of contaminant irradiation in vapor is primarily a function of the power of the electron beam. In this process, organic by-products, such as chloromethane, dichloromethane, chloroform, acetone, and trimethylbenzene, may be formed at very low concentrations (Matthews et al., 1992).

This technology was tested at the Building 834 Complex in November and December 1991 to destroy TCE. In this experiment, 90% of the influent TCE was destroyed at a cost of approximately $15/kg (Webster-Scholten, 1994). The demonstrated cost effectiveness of this technology resulted partly because of the high contaminant concentrations.

C-2.4. Disposal of Treated Vapor

Treated vapor from soil vapor extraction systems can be discharged to the atmosphere under permit by the San Joaquin Valley Unified Air Pollution Control District. Emissions from the treatment system are monitored for compliance with permit requirements.

C-2.5. Disposal of Treatment Waste

LLNL typically ships spent GAC offsite to be recycled at a GAC regeneration facility. The regeneration process is generally achieved through thermal reactivation. Thermal reactivation is conducted in a furnace where temperatures of up to 1800˚F are obtained. The advantage of thermal reactivation is that the organic contaminants are driven off the carbon and thermally destroyed (Nyer, 1992). Following regeneration, the GAC can be recovered for further use.

C-2.6. Soil and Rock Removal/Excavation

Excavation is a common method of removing near-surface contaminated earth materials by using conventional earth-moving equipment. In some cases, excavation is the only practical technology, particularly for small volumes of soil that contain contaminants such as PCBs or metals that cannot easily be treated *in situ*. Excavated materials can be treated on site or transported to an appropriate waste disposal facility.

Depending on the quantity of material to be excavated and the depth of excavation, different types of equipment can be used. The methods used for excavation are not greatly affected by the types of contaminants present. Determination of the extent of material to be excavated is one of the most difficult aspects of this technology. In most cases, collection and analysis of sediment samples are required during the excavation, adding considerably to the cost. In addition, the more indurated or cemented the sediment, the more difficult it is to excavate. Transport and

disposal of excavated material can be very costly if large volumes are involved (Isherwood et al., 1991).

C-2.7. Disposal of Excavated Soil and/or Waste

As discussed in Chapter 3, excavated material may either be transported to an off-site permitted facility for treatment, destruction, and/or disposal, or placed in an on-site containment unit. These disposal options are discussed below.

C-2.7.1. Off-site Disposal

The advantages of off-site waste disposal include:

1. Costs may be lower than for on-site disposal if the volume of excavated material is relatively low or if there are significant obstacles present during the siting, approval, or funding process for an on-site containment unit.

2. Waste disposal and containment can be achieved more quickly.

3. No long-term monitoring and maintenance would need to be conducted by DOE.

The logistics of transporting low-level radioactive waste off site would need to be addressed.

C-2.7.2. On-site Containment

On-site containment may be more cost effective than off-site disposal, particularly if large volumes of waste are excavated. On-site containment would involve the design and construction of an engineered containment unit. Components of the containment unit would include: (1) impermeable liners designed to prevent contaminant releases from the waste from infiltrating to the subsurface, (2) a leachate collection system to collect and remove leachate generated in the containment unit, and (3) a leak detection system designed to detect failure of the containment unit resulting in contaminant releases. As noted in Chapter 2, regulations in Title 22 and 23 of the California Code of Regulations (CCR) pertaining to waste/hazardous waste landfills have been identified as relevant and appropriate requirements. These requirements would need to be considered in designing, constructing, and maintaining an on-site containment unit(s).

C-2.7.2.1. On-site Containment Options. As mentioned in Chapter 3, the following two options have been identified for siting an on-site containment unit:

1. Construction of a containment unit at the location of an existing pit(s),

2. Construction of a containment unit at a new location in a "clean," uncontaminated area.

Each option has associated advantages and disadvantages. Construction of the containment unit in an existing pit area would avoid disturbing a clean area. However, in the case of the Pit 7 Complex, the underlying geologic and hydrogeologic conditions are not optimum for a containment unit. The waste material contained in the Pit 7 Complex landfills are periodically saturated by rising ground water. Another location with more suitable hydrogeologic conditions for the containment unit may potentially be found, although there are regulatory constraints that might be triggered by constructing the containment unit in a clean area.

Depending on the constituents, contaminated soil or pit material excavated for the purpose of contaminant source removal might be subject to hazardous waste regulations under CCR, Title 22, including land disposal restrictions. Treatment standards are a component of land disposal restrictions. The pits at Site 300 contain debris that would likely make waste treatment and compliance with treatment standards difficult. It should be noted that the State of California has been authorized by the U.S. EPA to implement the requirements of the Resource Conservation and Recovery Act (RCRA). Because California is a RCRA-authorized state, the federal hazardous waste regulations promulgated by U.S. EPA pursuant to RCRA are incorporated in the State hazardous waste regulations. However, regulatory mechanisms exist which allow for the management of remediation waste without triggering land disposal restrictions and the associated treatment standards. These mechanisms include U.S. EPA's area of contamination (AOC) policy and corrective action management units (CAMUs).

AOC Policy

Based on the U.S. EPA's AOC policy, wastes can be consolidated within a contiguous area of contamination without triggering land disposal restrictions. The AOC policy only covers consolidation and *in situ* management techniques carried out within an AOC. This policy would apply to the placement of waste in a containment unit constructed at the location of an existing pit.

CAMU Regulations

CAMUs differ from the AOC policy because they allow for the placement of remediation waste in uncontaminated areas at a facility and allow for consolidation of wastes from areas that are not contiguously contaminated.

Siting of the on-site containment unit in a clean area of Site 300 would require the designation of a CAMU. CCR, Title 22, Section 66264.552 and 40 Code of Federal Regulations 264.552, specify the requirements for CAMUs. One of the requirements is that the CAMU can include uncontaminated areas of the facility only if including such areas for the purpose of managing remediation waste is more protective than management of such wastes at contaminated areas of the facility [Title 22, CCR, Section 66264.552(c)(3)].

CAMUs are a type of RCRA unit that are designated and approved using permitting procedures, such as a facility permit or corrective action order. In the case of Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) cleanups, such as at Site 300, CAMUs may be approved as an applicable or relevant and appropriate requirement using a Record of Decision. U.S. EPA suggests that public notice of the tentative approval of a CAMU could be combined with public notice of a proposed plan**.**

U.S. EPA promulgated the final CAMU rule on February 16, 1993. Shortly after promulgation, a petition for review of the final CAMU rule was filed with the U.S. Court of Appeals (Environmental Defense Fund v. EPA). The petitioners challenged both the legal and policy basis for the final CAMU regulations. This litigation is pending and the outcome of the litigation could impact the current federal and California CAMU regulations. Changes to the CAMU regulations, that may be promulgated as a result, may limit the feasibility of designating a CAMU at Site 300.

C-2.7.2.2. Factors Affecting Implementation of an On-site Containment Unit. The feasibility and/or practicality of implementing the on-site containment unit may also be limited by several other factors. These factors include: (1) the waste classification and applicable ARARs, (2) the volume of waste for disposal, (3) hydrogeologic, biological, and topographic considerations, (4) DOE regulations and institutional requirements, (5) congressional funding and cost considerations, and (6) community acceptance. These factors will affect the time, resources, and costs associated with the implementation of the disposal options and therefore, determine the relative implementability of each option.

Waste Classification

The type or classification of waste to be placed in the containment unit, and the requirements of the applicable regulations, will affect the level of effort, resources and time necessary to obtain approval or permit, site, design, construct, and maintain the facility. If the waste is classified as hazardous waste, it would be subject to the substantive requirements of the hazardous waste regulations under CCR, Title 22 and the standards for discharges of waste to land under Title 23 CCR. If the waste is classified as low-level radioactive or mixed waste, the waste would also be subject to the requirements of the DOE regulations for management of radioactive waste (DOE Order 435.1). As a CERCLA site, it is not required to obtain permits under these regulations. However, it would be necessary, at a minimum, to meet the substantive requirements of these regulations for the siting, design, construction, monitoring, and maintenance of the waste containment unit. In addition, the process would be subject to regulatory review and approval and public input under CERCLA. The time and resources necessary to complete this process could significantly impact both the cost and time to implement an on-site disposal option.

Waste Volume

The volume of waste that must be excavated to achieve source control will affect the relative cost-effectiveness of the waste disposal. If a relatively small volume (less than 6,000 yd^3) of waste is generated through excavation, it may be more cost effective to transport and dispose of the waste at an off-site facility than to obtain approval for, site, construct, monitor, and maintain an on-site containment unit.

Siting Considerations

Hydrogeologic, biological, and topographic considerations may limit the possible locations for an on-site containment unit. Much of Site 300 is steep, rugged, terrain that is subject to landslides and erosion which limits the available area which is sufficiently flat-lying and stable enough to site a containment unit. Areas of critical habitat for endangered species present at Site 300 would need to be considered during siting evaluations. Depth to ground water and surface water drainage courses would also be important siting considerations to prevent ground water inundation or surface runoff infiltration into the containment unit.

DOE Requirements

DOE facilities are subject to numerous specific regulations, requirements, controls and limitations that could affect the implementation of on-site containment unit. For example, the siting of an on-site unit would require the development of a Conceptual Design Report which must be approved through several integrated processes to ensure the proposed land use is

consistent with the LLNL Institutional Plan and the Site 300 Comprehensive Plan. DOE would also require revision of the LLNL Environmental Impact Report/Environmental Impact Statement (EIR/EIS) and/or preparation and approval of facility-specific EIR/EIS for the containment unit facility. These processes could significantly impact the period of time and cost necessary to install an on-site containment unit. For example, the preparation, review, and approval of the LLNL Site 300 EIR/EIS took more than two years. The preparation and approval process for an EIR/EIS involves the following steps:

1. Determination of Lead Agency (2 – 4 weeks)

2. Preparation of Scoping Document (1 month)

3. DOE review of Scoping Document (1 month)

4. DOE issues the Notice of Intent (2 – 4 weeks)

5. Public Comment Period and Conduct Public Scoping Meetings (30 – 45 days)

6. Conduct Analysis and Prepare Draft EIR/EIS (4 – 6 months)

7. DOE review of Draft EIR/EIS (1 month)

8. DOE issues the Public Notice (2 – 4 weeks)

9. Public Comment Period and Public Hearings (45 – 60 days)

10. Prepare Final EIR/EIS (2 – 6 months)

11. DOE publishes Notice of Determination (2 – 4 weeks)

Times presented for the completion of each of these steps are estimated based on prior EIR/EIS experience.

Funding

The nature of DOE funding may affect the cost, scope, and logistics of implementing the on-site containment unit. The funding for DOE Environmental Restoration projects is allocated by Congress on an annual basis. Annual funding limitations may require that the work to excavate waste and construct an on-site containment unit be implemented in a phased approach over several years if a large volume of waste requires removal. The phased approach may increase the scope of work and associated costs.

Public Acceptance

Public acceptance may also affect the implementability of an on-site re-consolidation containment unit or CAMU containment unit. Residential development is encroaching on the once remote Site 300, which may increase public concern over future land and ground water use issues and construction of a waste containment unit at the site. At other sites, public opposition has been voiced against the use of on-site containment units. However, EPA's Technical Assistance Grant group has shown a preference for a properly constructed above-ground on-site containment structure.

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